Integrating Scientific Disciplines for Automated Command Support in High-Risk Missions

LtCol Dr. Arne Worm M.Sc. Ph.D.
Swedish Defence Research Agency
Command and Control Systems Division
P.O. Box 1165
SE-581 11 Linköping
SWEDEN

SUMMARY

In military operations and emergency management, operators and commanders must rely on distributed and automated systems for safe and effective mission accomplishment. Commanders and other decision makers must manage true real time system properties at all levels; individual operators, stand-alone technical systems, higher-order integrated human-machine systems and joint operations forces alike. In these high-risk, dynamical circumstances, management and utilisation of automated command support can rapidly become an unmanageable endeavour. Coping with automation issues in command and control is a challenge for practitioners and researchers. New results, new measurement techniques and new methodological advances facilitate a more accurate and deeper understanding, generating new and updated models. This in turn generates theoretical advances. This paper reports on research from which the results led to a breakthrough: An integrated approach to information-centred systems analysis to support automation research and development in command and control.

INTRODUCTION

In military operations and emergency management, mission performance relies increasingly on distributed organizations and automated systems to attain high safety and effectiveness without risking excessive resource depletion. The nature of such complex dynamic processes and operations are high-risk activities, where human and artificial team players, widely distributed across the whole theatre of operations, together perform tasks requiring extreme mobility, efficiency, agility and endurance. The units function autonomously for certain time periods and in specific areas, but primarily they are forced to co-ordinate their actions with one another. Management and utilisation of automated subsystems and command functions will be part of the daily routine.

Humans are required to monitor and maintain the conditions for safe and effective operation of systems like never before. Human operators have to cope with poorly structured and imprecise knowledge, by employing a diversity of human problem solving activities. In some cases the results are interpreted and converted into physical control signals to control and influence some physical process. In other cases the results are implemented as orders, containing plans, tactics and procedures for other humans or artefacts in other parts of an organisation to follow. Consequently, a number of issues naturally come to mind concerning the humans and the artefacts over which other humans must exercise control. Progress in information technology generates systems that enable a significant growth in the amount of information available for judgement and decision-making. Even the highest quality information will generally be associated with considerable uncertainty, ambiguity, inaccuracy and other deficiencies. There is a major need to link information with experiential context in ways such that it generates knowledge useful for judgement, scrutiny and selection.

Paper presented at the RTO HFM Symposium on "The Role of Humans in Intelligent and Automated Systems", held in Warsaw, Poland, 7-9 October 2002, and published in RTO-MP-088.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **00 OCT 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Integrating Scientific Disciplines for Automated Command Support in High-Risk Missions**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Swedish Defence Research Agency Command and Control Systems Division P.O. Box 1165 SE-581 11 Linköping SWEDEN**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001577., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

On the battlefield or on the disaster site commanders and operators are forced to routinely handle highly ambiguous decision situations, leaving them with meagre capacity to handle critical demands on cognitive abilities and response time. Managing conditions like uncertain evidence, ambiguous information, time pressure, feedback delays and highly dynamic circumstances is a risky endeavour for distributed teams with limited information exchange abilities. The smallest action can trigger dreadful consequences. Goal conflicts frequently occur and must be resolved with no external support. This is a challenge for any high-performance organisation with limited resources. Part of the problem is caused by the fact that technological advances have made the retrieval, production and distribution of information so much easier than before. Whereas information used to be scarce, and having more of it was considered a good thing, it seems that we now have reached the point of saturation, and need to limit our use of it. The commander used to say to his staff: – Give me all the facts! The commander sometimes tells his staff today: – Turn off those displays and give me a paper map, grease pens and some acetate sheets!

Technological advances have reduced the natural selection processes that would otherwise have kept all but the most important information from being taken into account. There is a significant increase in clumsy use of technology (Norman, 1988; Woods & Sarter, 1993; Sarter et al., 1997), generating new problems for the users:

1. Instead of freeing up cognitive resources, clumsy use of technology creates new kinds of cognitive work.
2. Instead of offloading tasks, autonomous, but silent machine agents create the need for team play, co-ordination and intent communication with people, demands which are difficult for automated systems to meet.
3. Instead of focusing user attention, clumsy use of technology diverts attention away from the job to the interface.
4. Instead of aiding users, generic flexibility creates new demands and requirements for the human operator to cope with.
5. Instead of reducing human erroneous actions, clumsy technology contains flaws that create the potential for unpredictable erroneous actions and assessments by users.
6. Instead of reducing knowledge requirements, clumsy technology demands new and more intricate knowledge and skills.

The result is an explosion in often irrelevant, unclear and inaccurate data fragments, making it ever more difficult to see the big picture (Morin, Jenvald & Worm, 1998a). In the domain of dynamic and complex systems, it is very important for an operator to have access to the big picture of the process. This helps the operator to step back and assess the overall system status, and decide where to look next within the system to acquire the next piece of information needed. Effects of excessive information load include anxiety, poor decision-making, difficulties in memorising and remembering, and reduced attention span. These effects merely add to the stress caused by the need to constantly adapt to a changing situation.

There is a need for a holistic view of the advantages and shortcomings of automated command and control support. Consequently, a number of research fields were reviewed: systems theory, decision-making and decision theory, leadership, psychophysiology, information theory and the science and systems of command and control.

THE ACTION CONTROL THEORY FRAMEWORK

The underlying principle was integration of well-established scientific disciplines into a new research direction, *Action Control Theory (ACT)*, a framework specifically composed to facilitate empirically based

conceptual modelling of dynamic, complex tactical systems and processes and of their states and state transitions. The research areas constituting ACT have until now developed along separate paths of evolution. However, now it is time to investigate what they might offer when implemented in an integrated, cohesive and coordinated manner. Flach & Kuperman (1998) concluded that it is essential to develop a unified, proactive, CSE-based approach in research and systems design for future warfare environments. We agree, and hold a strong belief in the power of integrative research approaches that are built on solid classical and innovative theoretical work, using comprehensive yet simple and robust conceptual and specific models of systems, tasks and missions, supported by advanced experimental and measurement methods and data analysis techniques.

The resulting models can be used for complex, multi-level human-machine systems design in the military, aviation and emergency response domains. Action Control Theory is a composite theoretical structure, derived from advances in:

1. Cognitive Systems Engineering (CSE).
2. Systems Theory, Control Theory and Cybernetics.
3. Decision Making in Complex Command and Control.
4. Psychophysiology.

THEORETICAL CONSTITUENT 1: COGNITIVE SYSTEMS ENGINEERING

The area of Cognitive Systems Engineering (CSE) has grown at an increasing pace since the first significant contributions were published in the 1980s by Rasmussen (1983; 1986), who introduced the concept of skill-based, rule-based and knowledge-based behaviour for modelling different levels of human performance. Hollnagel & Woods (1983) made a significant contribution to this field by their definition of a *Cognitive System* (CS) as a Man-Machine System (MMS) whose behaviour is goal-oriented, based on symbol manipulation and uses heuristic knowledge of its surrounding environment for guidance. A CS operates using knowledge about itself and the environment to plan and modify its actions based on that knowledge. According to Hollnagel (1999), the definition has been revised over the years in order to comprise new findings in human-machine systems research and to cover a more comprehensive and fundamental set of system properties: what the system *achieves*, what *objectives* it serves and what its *intentions* are. The current definition describes a CS as a system that can modify its pattern of behaviour on the basis of past experience in order to achieve specific anti-entropic ends. For example, in Command and Control (C^2) tasks in military missions a multitude of sensor systems, communication systems, training programs, personnel and procedures are all elements of the total operational system. Viewing this system as a CS permits the integration of all existing control resources; operators, commanders, technological facilities, doctrine, tactics, techniques and procedures, organization and training into a coordinated system that safely and efficiently achieves its mission. The use of CSE to model, analyse, and describe such systems performing hazardous, real time, high-stake activities is a powerful approach, given a sufficient understanding by the investigator of the interdependencies and linkages between other research areas and the CSE field.

THEORETICAL CONSTITUENT 2: SYSTEMS THEORY, CONTROL THEORY AND CYBERNETICS

From the work of Ashby (1956), Conant & Ashby (1970), and many others it is well known that most complex systems have *real-time, dynamic properties*; the system output at a given time is not only dependent of the input value at this specific time, but also on earlier input values, and that a good regulator of a system has to implement a model of the system that is to be controlled. According to Worm, (2000), the combined view of control theory in technical as well in behavioural domains is crucial for success in

this research area. When a function is implemented at one level of abstraction, represented at a second level of abstraction and controlled at a third level of abstraction the requirement for timely and complete information varies accordingly. On the other hand, it is not important whether an automated system under higher-order supervision or a highly qualified operator carries out a function or mission, the operators and the supervisory controllers still need to maintain an adequate situation understanding. In most situations the active agents in a dynamic system, such as soldiers/operators and their closest commander or squad leader, operate in a time scale of seconds to minutes. Their commanders and their command and control systems operate in time scales of hours to days. The key issue is to implement a system theory-based framework to cope with such dynamic properties, and of the environments such systems operate in. The mathematical stringency and powerful formalism of systems theory makes it possible to describe and treat systems as diverse as technical, organizational, economic and biological dynamic systems in basically the same manner: as processes, or clusters of processes, with a built-in adherent or assigned control system.

According to Conant & Ashby, (1970), Glad & Ljung, (1989) and Brehmer, (1992), four fundamental requirements must be met, if control theory should be used successfully in analysis and synthesis of dynamic systems:

1. There must be a goal (*the goal condition*).
2. It must be possible to ascertain the state of the system (*the observability condition*).
3. It must be possible to affect the state of the system (*the action condition*).
4. There must be a model of the system (*the model condition*).

The mission objectives and the goals for the joint cognitive system construct one of the four principal components of systems control, the goal condition. Thus, the surrounding contextual information and the experiential familiarity of the information users are most important. It is the use of information within the context of contingencies in the mission and the environment that results in the transformation from information to knowledge, which is then interpreted in terms of context and experience by sensing situations and recognising patterns. We form an internal system model, which is a homomorphic system representation to fulfil the model condition. This model conceptualises what we are supposed to achieve, with what resources, within what timeframe, while simultaneously considering what we will be challenged with once the imminent situation is resolved.

From observations of the mission environment and securing our own capabilities to act in a way that the system state progresses in a desirable manner to meet the objective (thereby fulfilling the observability and action conditions), we recognise characteristics similar to previously endured situations. We also simplify the problem by using our previous experience and professional skills to construct internal models, hypotheses, or schemata to use for feedforward control on a temporary basis. We employ simplified deductions, “rules of thumb”, based on these hypotheses and execute appropriate actions according to those deductions. Outcome feedback from these actions aimed at influencing the mission environment enables us to learn more about the environment and the nature of the forthcoming course of action in the mission. We rework our hypotheses, reinforcing appropriate ones and rejecting poor ones in order to augment and refine our internal system model.

THEORETICAL CONSTITUENT 3: DECISION MAKING IN COMPLEX COMMAND AND CONTROL

The conventional and classic *Analytical Decision Making* approach, supported by normative theories, reduces decision making to selecting an appropriate action from a closed, pre-defined action set, and to resolution of conflicts of choice. Hence, the analysis of decision tasks concentrates on the generation of

alternatives and the evaluation of these alternatives according to some criterion, usually expected value. According to Lehto (1997), Cohen et al. (1998), Wickens (1992) and Kleindorfer et al. (1993), the most familiar classical framework for decision making contains two main parts: *Bayesian probability theory* for drawing inferences about the situation at hand, and *Multiattribute Utility Theory* for selecting an optimal action. There is a lot to be said about analytical, mono-theoretical approaches, especially when investigators and researchers claim they have a stringent and formal theory which "takes care of it all" regarding the host of requirements in need of fulfilment for the theory to hold in a real-world decision situation.

Brehmer (1992) suggested the use of control theory as a framework for research in *Distributed, Dynamic Decision Making*. Brehmer's research was based on analysis of several applied scenarios, e.g. military decision making, operator tasks in industrial processes, emergency management and intensive care (Brehmer, 1988; 1992). The following results were clarified in these analyses:

1. The decision-making was never the primary task. It was always directed towards some goal.
2. A series of decisions is required to reach the goal.
3. The decisions are mutually dependent.
4. The state of the decision problem changes, both autonomously and as a consequence of the decision-maker's actions.
5. The situational dynamics require decisions to be made in real time.

Naturalistic Approaches to Decision Making

Zachary & Ryder (1997) reviewed decision-making research during the last decades. They elaborated on the major paradigm shift in decision theory from the analytic, normative decision making procedures of von Neumann & Morgenstern (1947), Simon (1955) and Newell and Simon (1972) to descriptive Naturalistic Decision Making (NDM) procedures, described by Klein (1989; 1993a; 1993b) as well as by Klein & Woods (1993) and Orasanu & Connolly (1993). NDM applies to many dynamic, safety-critical and even dangerous areas of activity such as tactical command and control in military missions, fire fighting, emergency response and medical diagnosis. The work of Zachary and Ryder relates strongly to Control Theory, Cognitive Systems Engineering, Dynamic, Distributed Decision Making, and Command and Control science, and presents a broad approach to decision support systems development and design. The essentials of this paradigm are condensed below:

1. Human decision-making should be studied in its natural context.
2. The underlying task and situation of a problem is critical for successful framing.
3. Actions and decisions are highly interrelated.
4. Experts apply their experience and knowledge non-analytically by identifying and effecting the most appropriate action in an intuitive manner.

Tactical Team Decision Making

Tactical decision-making teams in the modern warfare environment are faced with situations characterized by rapidly unfolding events, multiple plausible hypotheses, high information ambiguity, severe time pressure, and serious consequences for errors (Cannon-Bowers et al., 1995). There are also cases when geographical separation or other forms of distributed environments in which the teams operate impose additional difficulties Brehmer (1991). To be able to adapt to these situations, team members must co-ordinate their actions so that they can gather, process, integrate, and communicate information timely and effectively. The accurate diagnosis of team performance shortfalls and the tailoring of subsequent training toward correcting these shortfalls for the team and individual team members require systematic

performance assessment from multiple perspectives. Unfortunately, it was the case in the past that operational systems either ignored performance measurement completely, or treated it in an unsystematic fashion. This was particularly true of complex systems where it was difficult to assess performance with a single correct answer, or in situations where there were several individual decision-makers forced to interact as a team.

THEORETICAL CONSTITUENT 4: PSYCHOPHYSIOLOGY

Traditionally, stress research has been oriented toward studies involving the body's reaction to stressors (a physiological perspective) and the cognitive processes that appraise the event or situation as a stressor (a cognitive perspective). However, current social perspectives of the stress response have noted that different people experiencing similar life conditions are not necessarily affected in the same manner. There is a growing interest in the epidemiology of diseases thought to result from stress. It has been noted that the incidence of hypertension, cardiovascular ailments, and depression varies with such factors as race, sex, marital status, and income. This kind of socioeconomic variation of disease indicates that the stressors that presumably dispose people toward these illnesses are somehow linked to the conditions that people confront through their history of varying occupational and social position and status in the society. The stress response is a warning of a homeostatic imbalance occurring (Levine and Ursin, 1991). This implies that the concept of *model error* from control theory once again can be applied. The stress response is also mobilizing physiological resources to improve performance, which is regarded as a positive and desirable warning response. The Cognitive Activation Theory of Stress (CATS) describes the phases of the stress response as an alarm occurring within a complex cognitive system with feedback, feedforward and control loops, no less but no more complicated than any other of the body's self-regulated systems (Eriksen et al., 1999).

Within joint cognitive systems performing complex, high-risk military and emergency response missions there is a fundamental and profound connection between human operator physiological stress response and discrepancies between expectancies and experiences. Decision-makers are not free to make decisions when they feel ready to do so. Instead, the environment requires decisions and the decision-maker, ready or not, have to make these decisions on demand. According to Brehmer (1991) this causes stress in dynamic decision-making tasks. In order to cope with this stress, decision-makers have to develop strategies for control of the assigned dynamic tasks and for keeping their own workload at an acceptable level. Coping strategies of individuals are primarily social in nature. The manner in which people attempt to avoid or resolve stressful situations, the cognitive strategies that they use to reduce threat, and the techniques for managing tensions are largely learned from the groups to which they belong. Although the coping strategies used by individuals often are distinct, coping dispositions are to a large extent acquired from the social environment.

MODELS: A HUMAN-CENTRED MODELLING STRATEGY

The success of automated Command and Control support depends not only upon computational speed and robustness, but also whether the designers have adequately supported the cognitive demands of the users' tasks and the impacts of technological change to the organisational processes. As noted earlier in this work, human-machine interaction and decision-making performance in critical situations are dramatically affected by the design of the user-artefact co-operation (e.g., task allocation, information sharing requirements, etc.) with respect to the environmental characteristics (e.g., complexity, uncertainty, dynamics, level of threat, etc.) and the response requirements (e.g., timing and precision). Woods & Roth (1988) propose that mismatches in the system design involving these factors result in the ineffective use of resources and, in the worst cases, disastrous system errors and failures. Woods & Roth cite several cases where automation degraded rather than improved performance due to user-related design failures such as a lack of support for supervisory control requirements and decision-making strategies, and failures to

anticipate the organisational impacts of technological change. This section presents several aspects of system design that can improve the overall effectiveness of the collaboration between human decision-makers and their technological system support.

We have already discussed the importance of models for systems control and situation understanding, and there are a number of lessons to learn from its more specialised applications in different areas, such as military operations, emergency response operations and air traffic control. When a function is implemented at one level of abstraction, represented at a second level of abstraction and controlled at a third level of abstraction the requirement for timely and complete information varies accordingly. On the other hand, if it is not important whether an operator or an automated system carries out a function or mission under higher-order supervision, the operators and the supervisory controllers still need to maintain an adequate situation comprehension, originating from a model of the system.

We will go a little deeper into some of the concepts introduced in the earlier sections, and begin with a more formal definition of what a model is.

A model is a system C ˜ [E, M, Y] constituted by:

1. A modelled system or mission environment E = f (E, L) with the total set E = $\{e_i\}$ of possible states that can occur, and possible actions or laws L: E ? E. For example, E could be the set of key presses of a computer operator or the physical world. Then L is the behaviour of the operator or the laws of nature.
2. A modelling system M = f (M, R) with internal model states or representations M = $\{m_k\}$, and a modelling function, which is basically a set of rules, R: M ? M. For example, M could be a numerical or symbolic data set, a sequence of neural signals or a reconstructed course of events in a mission. Then the rules R are the processing activity of a computer, the synaptic electrochemical transmissions between a network of neurons, or the decisions, orders and actions of the unit commander and his staff.
3. A representation function Y: E ? R. For example, Y = $\{y_n\}$ could be a measurement vector, a perception, or an observation.

When the functions L, R, and E commute, then we have $m_k = R(m_{k-1}) = R(Y(e_{i-1})) = Y(L(e_{i-1})) = Y(e_i)$. Under these conditions C is a good model, and the modelling system M can sufficiently predict the behaviour of the mission environment E. Then C is called a generator of predictions about E. On the other hand, there exists a possibility that M is a model itself, implying that C in that case is a meta-model. In that case C does not generate a prediction directly. Instead it generates another model, which in turn is capable of generating predictions at other levels of abstraction, aggregation and complexity. Hence the notion of situation understanding can be described as a hierarchical knowledge structure, recursively generating predictions about the world and itself, thereby empowering the cybernetic system (cognitive system, agent) to make decisions about its actions.

Mental Representations

According to Rouse et al. (1992) and Rouse et al. (1993) the importance of accurate and comprehensive mental models cannot be overestimated. A mental model synthesizes the steps of a process, and organizes them as a unit. Allen (1997) described the main evidence of people developing and utilizing mental models as follows:

1. *Prediction* of process steps and future course of events.
2. *Explanation* of the cause of an event.
3. *Diagnosis* of the reasons for malfunction.
4. *Training* of operators, maintainers and other users.

To be able to share, develop and discuss mental models together with other people, *conceptual models*, i.e., models of mental models are of great help. Allen (1997) described various classes of conceptual models: metaphors, surrogates, mappings, task-action grammars, plans and propositional knowledge. The model condition, or Conant's and Ashby's law of required model-regulatory identity (Conant and Ashby, 1970), that stipulates that every good regulator of a system must be a model of that system, is of course also valid when mental models are considered. This was commented by Hollnagel (1999) who described the importance of Ashby's law of requisite variety to mental model development and minimisation. Hollnagel advocated a cybernetic or functional approach to modelling of human operators and of the mental models of their surrounding environment. A mental model can be seen as the basis for generating input to a system, in order to keep the variety of the system within given limits.

Tactical Joint Cognitive Systems

The point of departure in this ACT-based systems modelling endeavour was the definition of a Tactical Joint Cognitive System (TJCS) as an aggregate of one or several instances of four principal sub-system classes:

1. *Technological Systems*, for example vehicles, intelligence acquisition systems, communication systems, sensor systems, life support systems, including the system operators.
2. *Command and Control Systems*, consisting of an information exchange and command framework, built up by technological systems and directly involved decision-makers.
3. *Support Systems*, comprising staff functions, logistic functions, decision support functions, organizational structures, and various kinds of service support.
4. *Tactical Teams*, composed and defined according to (Salas et al., 1992) as: "Two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have been assigned specific roles or functions to perform, and who have a limited life-span of membership."

Mission Execution and Control Models

The next step was integration of these concepts into a Tactical Action COntrol Model (TACOM). The principal components of the TACOM are the Mission Environment, the Tactical Joint Cognitive System, the Situation Assessment function, and the Cognitive Action Control function, derived primarily from the work of Brehmer (1988; 1992), Klein (1993a; 1993b) and Worm (2000; 2001a; 2002). From the TACOM the Mission Execution and Control Model (MECOM) is constructed. The MECOM consists of one or several TACOMs extended with control-theoretic components, to handle system disturbances, model error, and to allow an adaptive and balanced mix of feedforward and feedback control. The last step in the model formation process is combining and aggregating several MECOMs into unilevel and multilevel MECOMs, respectively.

METHODS: THE TRIDENT PROJECT

We have for several years conducted methodological development in the Tactical Real-time Interaction in Distributed EnvironmeNTs (TRIDENT) project to support the modelling work (Worm, 2001b). The primary objective of TRIDENT is to develop a coherent and straightforward package of theoretically sound and empirically validated methods and techniques for human-machine systems analysis in the setting of tactical mission scenarios. The components of TRIDENT are summarised below:

1. Using the Action Control Theory (ACT) Framework for conceptual modelling of dynamic, complex tactical systems and processes, of their states and state transitions.

2. Identification of mission and unit state variables, and of action control and decision making mechanisms for process regulation.
3. Mission Efficiency Analysis (Worm et al., 1998; Worm, 2001a; 2001b) of fully manned and equipped units executing full-scale tactical missions in an authentic environment.
4. Measuring information distribution and communication effectiveness.
5. Measuring workload by means of the NASA Task Load Index (Hart & Staveland, 1988).
6. Assessing team member psychosocial mood by means of the Mood Adjective CheckList (MACL, Sjöberg et al., 1979).
7. Assessing situation awareness (Endsley, 1995) as a function of mission-critical information complexity (Svensson et al., 1993).
8. Measuring level and mode of cognitive, context-dependant control of the team members, and identifying what decision strategies were utilised by the team and team members.
9. Applying reliability and error analysis methods for investigating failure causes both in retrospect and for prediction (Hollnagel, 1998).
10. Validating identified constructs and measuring their influence using advanced data analytic procedures.

STUDIES

Numerous battle management and emergency response studies have been carried out in which we used every opportunity to test, refine and augment the modelling, measurement, data collection and analysis concepts of TRIDENT. Implementing these ideas for tactical mission analysis in potentially dangerous, stressful and cognitively complex environments showed to be very effective.

Using the TRIDENT concepts for analysis and evaluation on aggregated system levels has so far been very rewarding, with high acceptance among the subjects; trained and skilled professionals performing their daily tasks in their accustomed work environment. However, we have also experienced some critique. It is occasionally claimed that reliability and validity of subjective workload ratings are insufficient. For that reason we considered incorporating a measure of workload and stress which is commonly accepted in the scientific community. We considered hormonal response measures, inspired by the results of Svensson et al. (1993), who studied workload and performance in military aviation, Zeier, (1994) who studied workload and stress reactions in air traffic controllers, and Holmboe et al. (1975), who studied military personnel performing exhausting battle training. We designed a study in order to elucidate to what extent hormonal physiological stress indications are linked to the rating, observation and data collection methods normally used in TRIDENT to assess workload and tactical performance. The details of the study are described in Worm (2000).

RESULTS

From the studies a number of particularly interesting causes of mission failure or poor performance could be identified. The predominant error modes were:

1. Timing of movement and of tactical unit engagement.
2. Speed of movement or maneuver, which is especially important in the initial phase of engagement.
3. Selection of wrong object. The environments of ground warfare or emergencies offer many opportunities for choosing wrong objects, in navigation, in engagements, or in visual contact.

After a retrospective cognitive reliability and error analysis using the Cognitive Reliability and Error Analysis Method (CREAM) developed by Hollnagel (1998) we found that mission failure or poor performance in every case could be attributed to:

1. Slow or even collapsed organizational response.
2. Ambiguous, missing or insufficiently disseminated, communicated and presented information.
3. Equipment malfunction, e.g. power failure or projectile/missile impact.
4. Personal factors: inexperience, lack of team training etc.

Empirical results suggest three potentially significant mechanisms influencing how the team is able to execute mission control, which consequently also influences mission efficiency:

1. Time-dependant filtering functions like defense and coping mechanisms according to the cognitive Activation Theory of Stress (Eriksen et al.; 1999, Levine & Ursin, 1991).
2. Performance limiting factors due to specific mission and task situation factors and resource requirements (Reason, 1997; Hollnagel, 1998; Worm, 2001a).
3. Balance between feedforward and feedback in mission-critical action control (Reason, 1997; Worm, 2000).

CONCLUSION

We have for a number of years struggled towards building a foundation for analysis and evaluation of high-stake, life-threatening tactical missions in various work contexts. Although earlier results indicate that a workable, reliable and valid result has been achieved, the question is still if the findings are generally applicable. The theoretical achievements were a complicated and arduous venture, in that we have constantly striven for empirical evidence. Nevertheless it is obvious that a scientific breakthrough has been achieved. We argue that the ACT / TRIDENT approach can be used as an advanced systems engineering support and will facilitate:

1. Identification of limiting factors of a specific individual, unit, system, procedure or mission.
2. Assessment of the magnitude of influence of these factors on overall tactical performance.
3. Generation and implementation of measures to assist, control and improve insufficient capabilities and contribute to successful accomplishment of future missions.
4. Methodological support in future integrated C3I systems.
5. Improving training programs for tactical decision-making and resource management.

Studying individuals is an effective, reliable and valid way to probe the function and efficiency of an organization, performing complex tasks in an ever-changing mission environment. We will continue to work with collected data, and use the results from the analysed scenarios to tune and adjust the theory, models and methods in order to obtain a coherent and cohesive framework for human-machine systems analysis of tactical mission settings and scenarios. We will also develop computerized versions of the test instruments, if possible with built-in tools for data analysis and graphical presentation, so that researchers and investigators not familiar with the background and early history of this project can benefit in their own work from our achievements.

REFERENCES

Allen, R.B., (1997). Mental Models and User models. In M. Helander, T.K. Landauer, & P. Prabhu. (Eds.) Handbook of Human-Computer Interaction, 2nd Ed. Elsevier Science B.V.

Ashby, W.R. (1956). An Introduction to Cybernetics. London: Chapman & Hall.

Brehmer, B. (1988). Organization of Decision Making in Complex Systems. In L.P. Goodstein, H.B. Andersen, & S.E. Olesen (Eds.), Tasks, Errors, and Mental Models. London: Taylor & Francis.

Brehmer, B. (1991). Time Scales, Distributed Decision Making, and Modern Information Technology. In J. Rasmussen, B. Brehmer, & J. Leplat (Eds.), Distributed Decision Making: Cognitive Models for Cooperative Work. Chichester: Wiley.

Brehmer, B. (1992). Dynamic Decision Making: Human Control of Complex Systems. Acta Psychologica, 81, pp. 211-241.

Cannon-Bowers, J.A., Tannenbaum, S.I., Salas, E., & Volpe, C.E. (1995). Defining Team Competencies and Establishing Team Training Requirements. In R. Guzzo & E. Salas (Eds.), Team Effectiveness and Decision Making in Organizations, pp. 333-380. San Francisco, CA: Jossey Bass.

Cohen, M.S., Freeman, J.T., & Thompson, B. (1998). Critical Thinking Skills in Tactical Decision Making: A Model and a Training Strategy. In J.A. Cannon-Bowers & E. Salas (Eds.), Making Decisions Under Stress: Implications for Individual and Team Training, pp. 155-189. Washington, DC: American Psychological Association.

Conant, R.C., & Ashby, W.R. (1970). Every Good Regulator of a System must be a Model of that System. International Journal of System Science, 1, pp. 89-97.

Endsley, M.R. (1995) Towards a Theory for Situation Awareness in Dynamic Systems. Human Factors, 37, pp. 32-64.

Eriksen, H.R., Olff, M., Murison, R., & Ursin, H. (1999). The Time Dimension in Stress Responses: Relevance for Survival and Health. Psychiatry Research, 85, pp. 39-50.

Flach, J.M., & Kuperman, G. (1998). Victory by Design: War, Information, and Cognitive Systems Engineering. (Report No. AFRL-HE-WP-TR-1998-0074). Wright-Patterson AFB, OH: Air Force Research Laboratory, Cre System Interface Division.

Glad, T., & Ljung, L. (1989). Reglerteknik. Grundläggande teori. [Automatic Control. Basic Theory.] Lund: Studentlitteratur.

Hart, S.G., & Staveland, L.E. (1988). Development of a Multi-Dimensional Workload Rating Scale: Results of Empirical and Theoretical Research. In P.A. Hancock & N. Meshkati (Eds.), Human Mental Workload. Amsterdam, The Netherlands: Elsevier Science B.V.

Hollnagel, E. (1998). Cognitive Reliability and Error Analysis Method (CREAM). Amsterdam, The Netherlands: Elsevier Science B.V.

Hollnagel, E. (1999). Modeling the Controller of a Process. Trans Inst MC, Vol. 21, No 4/5, pp. 163-170.

Hollnagel, E., & Woods, D.D., (1983). Gognitive Systems Engineering: New Wine in New Bottles. International Journal of Man-Machine Studies, 18, pp. 583-600.

Holmboe, J., Bell, H., & Norman, N. (1975). Urinary Excretion of Catecholamines and Steroids in Military Cadets Exposed to Prolonged Stress. Försvarsmedicin, 11, p. 183.

Klein, G.A. (1989). Recognition-Primed Decisions. In W. Rouse (Ed.), Advances in Man-Machine Systems Research, 5, pp. 47-92. Greenwich, CT: JAI Press, Inc.

Klein, G.A. (1993a). Naturalistic Decision Making – Implications for Design. State-of-the-Art Report. Dayton, OH: Crew Systems Ergonomics Information Analysis Center, Wright-Patterson Air Force Base.

Klein, G.A. (1993b). A Recognition-Primed Decision (RPD) Model of Rapid Decision Making. In G.A. Klein, J. Orasanu, R. Calderwood, & C.E. Zsambok (Eds.), Decision Making in Action: Models and Methods. Norwood, NJ: Ablex.

Klein, G.A., & Woods, D.D. (1993). Conclusions: Decision Making in Action. In G.A. Klein, J. Orasanu, R. Calderwood, & C.E. Zsambok (Eds.), Decision Making in Action: Models and Methods. Norwood, NJ: Ablex.

Kleindorfer, P.R., Kunhreuther, H.C. & Schoemaker, P.J. (1993). Decision Sciences. An Integrative Perspective. Cambridge: Cambridge University Press.

Lehto, M.R. (1997). Decision Making. In G. Salvendy (Ed.), Handbook of Human Factors and Ergonomics, 2nd Ed., pp. 1201-1248. New York, NY: Wiley.

Levine, S., & Ursin, H. (1991). What is Stress? In M.R. Brown, G-F. Koob, & C. Rivier (Eds.), Stress – Neurobiology and Neuroendocrinology. Marcel Dekker, New York, pp. 3-21.

Morin, M., Jenvald, J., & Worm, A. (1998), Training Emergency Management and Response: Creating the Big Picture. In Proceedings of The International Emergency Management Society 1998 Annual Conference, Washington, DC, USA.

Newell, A., & Simon, H.A. (1972). Human Problem Solving. Englewood Cliffs, NJ: Prentice-Hall.

Norman, D.A. (1988). The Psychology of Everyday Things. New York: Basic Books.

Orasanu, J., & Connolly, T. (1993). The Reinvention of Decision Making. In G.A. Klein, J. Orasanu, R. Calderwood, & C.E. Zsambok (Eds.), Decision Making in Action: Models and Methods, pp. 3-20. Norwood, NJ: Ablex Publishing Corporation.

Rasmussen, J. (1983). Skills, Rules, and Knowledge: Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. IEEE Transactions on Systems, Man, and Cybernetics, SMC-13, pp. 257-266.

Rasmussen, J. (1986). Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering. New York: North-Holland.

Reason, J. (1997). Managing the Risks of Organizational Accidents. Ashgate.

Rouse, W.B., Cannon-Bowers, J.A., & Salas, E. (1992). The Role of Mental Models in Team Performance in Complex Systems. IEEE Transactions on Systems, Man, and Cybernetics, 22, pp. 1296-1308.

Rouse, W.B., Edwards, S.L., & Hammer, J.M. (1993). Modeling the Dynamics of Mental Workload and Human Performance in Complex Systems. IEEE Transactions on Systems, Man, and Cybernetics, 23, pp. 1662-1671.

Salas, E., Dickinson, T.L., Converse, S.A., & Tannenbaum, S.I. (1992). Toward an Understanding of Team Performance and Training. In R.W. Swezey and E. Salas (Eds.), Teams: Their Training and Performance, pp. 3-30 Norwood, NJ: Ablex Publishing Corporation.

Sarter, N.B., Woods, D.D., & Billings, C.E. (1997). Automation Surprises. In G. Salvendy (Ed.), Handbook of Human Factors and Ergonomics, 2nd Ed., pp. 1926-1943. New York: Wiley.

Simon, H.A. (1955). A Behavioral Model of Rational Choice. Quarterly Journal of Economics, 69, pp. 99-118.

Sjöberg, L., Svensson, E., & Persson, L.-O. (1979). The Measurement of Mood. Scandinavian Journal of Psychology, 20, pp. 1-18.

Svensson, E., Angelborg-Thandertz, M., & Sjöberg, L. (1993). Mission Challenge, Mental Workload and Performance in Military Aviation. Aviation, Space and Environmental Medicine, Nov., pp. 985-991.

Von Neumann, J., & Morgenstern, O. (1947). Theory of Games and Economic Behavior. Princeton, NJ: Princeton University Press.

Wickens, C.D. (1992). Engineering Psychology and Human Performance. (2nd Ed.) New York: HarperCollins.

Woods, D.D., & Roth, E.M. (1988). Cognitive Engineering: Human Problem Solving with Tools. Human Factors, 30, pp. 415-430.

Woods, D.D., & Sarter, N.B. (1993). Evaluating the Impact of New Technology on Human-Machine Cooperation. In J.A. Wise, V.D. Hopkin, & P. Stager (Eds.), Verification and Validation of Complex Systems: Human Factors Issues. New York: Springer-Verlag.

Worm, A. (2000). On Control and Interaction in Complex Distributed Systems and Environments. Linkoping Studies in Science and Technology, Dissertation No. 664, Linkoping University, Linkoping, Sweden. ISBN 91-7219-899-0.

Worm, A. (2001a). Tactical Mission Analysis by Means of Naturalistic Decision Making and Cognitive Systems Engineering. In E. Salas & G.A. Klein (Eds.). Linking Expertise and Naturalistic Decision Making, pp. 407-431. Mahwah, NJ: Earlbaum. ISBN: 0-8058-3538-5.

Worm, A. (2001b). On Systems Analysis and Performance Assessment in Complex, High-Risk Work Environments. Int. J. Risk Assessment and Management, Vol. 2, Nos. 3/4, pp. 276-287. Inderscience, Switzerland.

Worm, A. (2002). An Integrated Framework for Information-Centered Human-Machine Systems Analysis. Int. J. Emergency Management, Vol. 1, No. 2, pp. 125-143. Inderscience, Switzerland.

Worm, A., Jenvald, J., and Morin, M. (1998). Mission Efficiency Analysis: Evaluating and Improving Tactical Mission Performance in High-Risk, Time-Critical Operations. Safety Science, 30, pp. 79-98. Elsevier Science B.V., The Netherlands.

Zachary, W.W., & Ryder, J.M. (1997). Decision Support Systems: Integrating Decision Aiding and Decision Training. In M. Helander, T.K. Landauer, & P. Prabhu. (Eds.) Handbook of Human-Computer Interaction, 2nd Ed. Elsevier Science B.V.

Zeier, H. (1994). Workload and Psychophysiological Stress Reactions in Air Traffic Controllers. Ergonomics, 37, pp. 525-539.

This page has been deliberately left blank

Page intentionnellement blanche